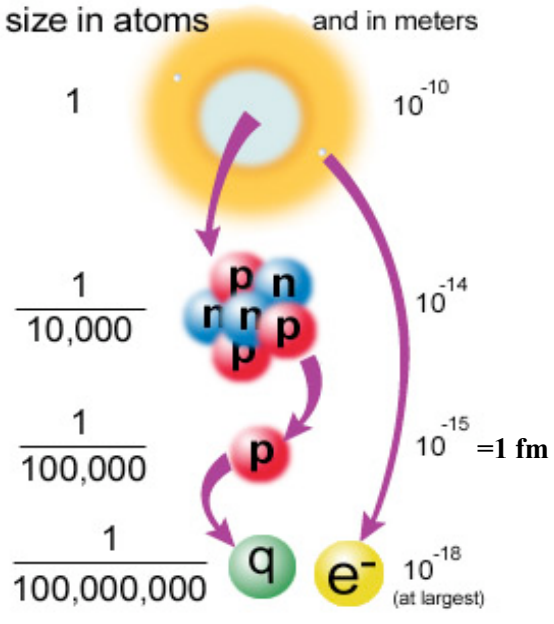
Particle Physics

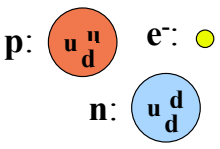
Outline :

- The Constituents of Ordinary Matter
- "Who Ordered the Muon ?"
- Forces & Unification
- The Higgs Boson
- Particle Physics is High Energy Physics
- Particle Physics & The Early Universe
- Accelerators & Detectors

The Constituents of Ordinary Matter



Almost all matter consists of "up" and "down" quarks and electrons ...

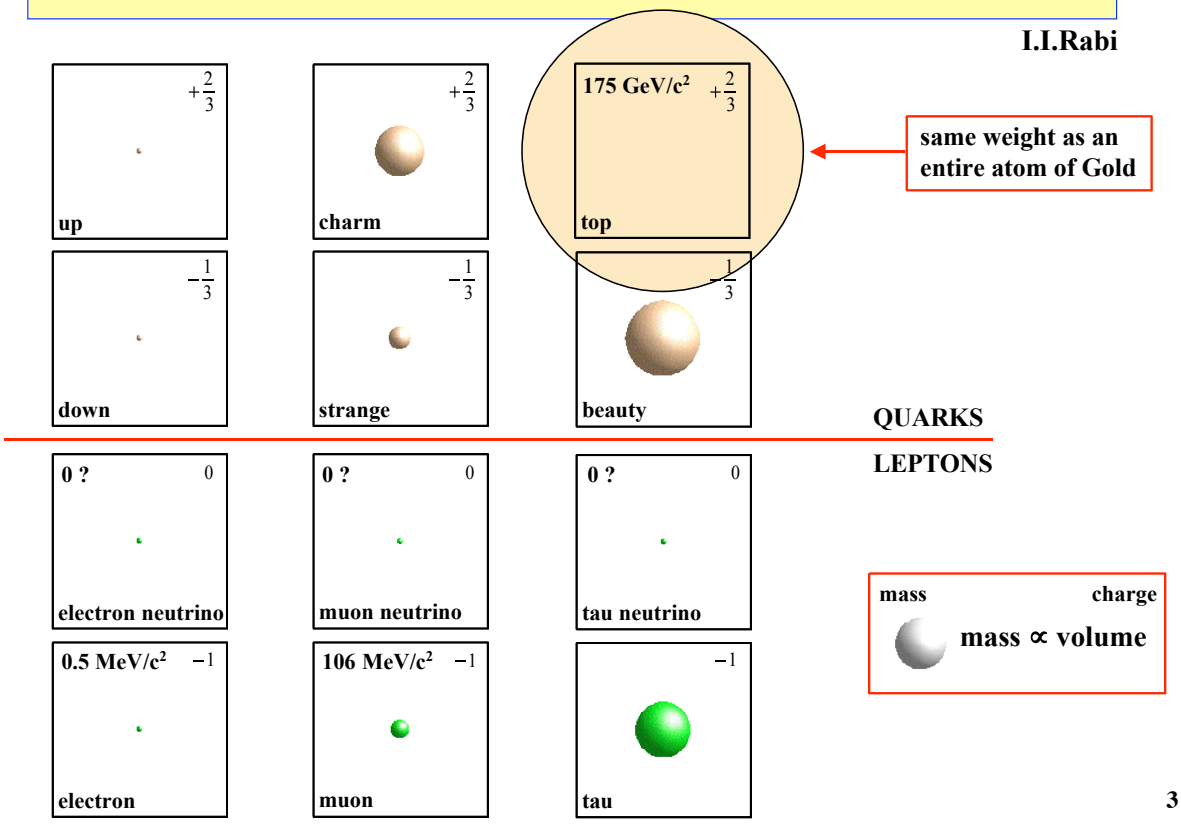


... and neutral electron counterparts "neutrinos" :

- Beta decay : $n \rightarrow p + e^- + \bar{\nu}_e$
- Fusion in the sun : $p + p \rightarrow d + e^+ + \nu_e$

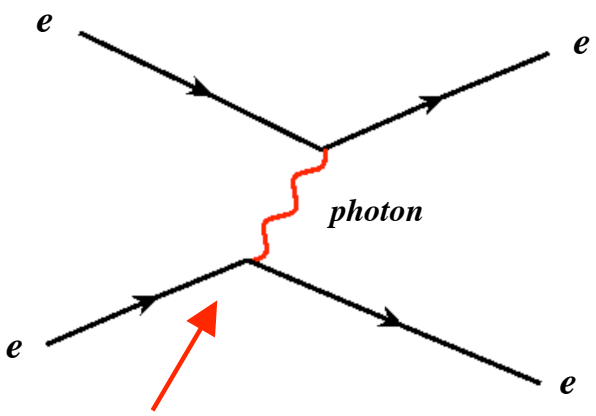
"Who Ordered the Muon ?"

I.I.Rabi

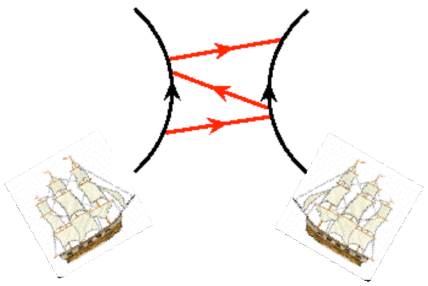


Forces

- We know from the photoelectric effect that the electromagnetic field is ***quantised*** : the energy in the field is "lumped" into photons, which are subject to the same quantum uncertainty as particles.
- A full quantum mechanical treatment of particles and fields needs to treat the interaction of field ***quanta*** with particles :



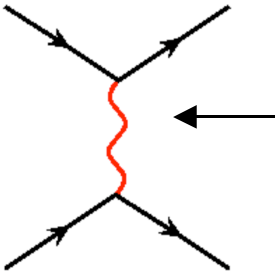
Electromagnetic interaction between two electrons.



Electrons deflected due to the momentum of the exchanged photon.
Analogy with ships exchanging cannon balls ⇒

Range of Forces

- Fluctuations in quantum fields are governed by the same uncertainty relationships we saw earlier for particles.
- For example, we can calculate the range of forces mediated by virtual particles of different masses.



Exchange particle has rest mass M_0

Energy that must be "borrowed" :

$$\Delta E = M_0 c^2$$

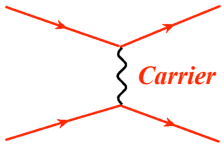
- The energy can be "borrowed" for a time dictated by the uncertainty principle :

$$\Delta E \, \Delta t \approx \hbar \quad \Rightarrow \quad \Delta t \approx \frac{\hbar}{\Delta E}$$

- Since the particle cannot travel faster than the speed of light, the maximum range is :

$$\text{Range} = c \times \Delta t \approx \frac{\hbar c}{M_0 c^2}$$

Forces of the Standard Model

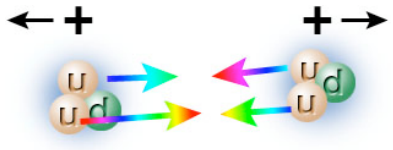


$$\text{Range} = c \times \Delta t \approx \frac{\hbar c}{M_0 c^2}$$

Force	Relative Strength	Carrier	Mass	Range	Felt By	Example
Electromagnetism	~10^{-3}	photon	0	∞		
Weak Nuclear	~10^{-5}	W, Z	80-90 GeV/c^2 (~100 × m_p)			
Strong Nuclear	~1	gluon	0			
Gravity	~10^{-38}	graviton				

The Strong Nuclear Force

- A residue of the strong interaction between quarks is responsible for binding nucleons together inside nuclei :



- The quantum theory of electromagnetism is called **QUANTUM ELECTRO-DYNAMICS**. It describes particles carrying ordinary electron charge.
- The corresponding theory of the strong nuclear force is called :

QUANTUM CHROMO-DYNAMICS

- It describes particles carrying "colour charge" :

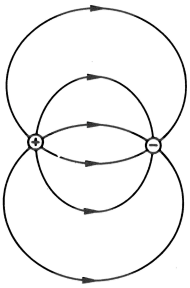
R G B

- Why is the strong nuclear force apparently short range ?
  - Between nucleons we are only seeing a Van der Waals residual force between colourless combinations of quarks.
- Why have we never found free quarks ?

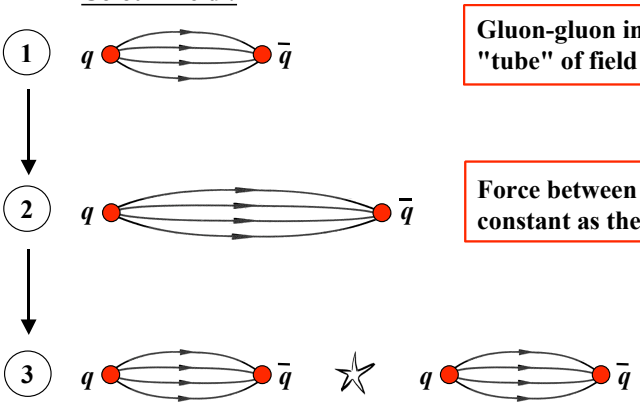
The Strong Nuclear Force

- The fact that free quarks are never found is a consequence of the fact that there is no "**bare colour**" in nature.
- Why not ? The vacuum screens the strong colour field :

Electric Field :



Colour Field :



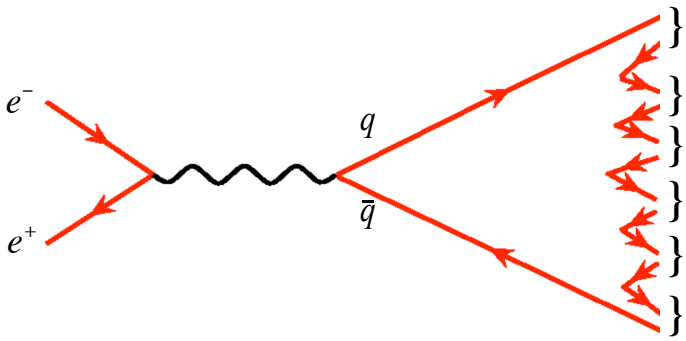
Gluon-gluon interaction forms a "tube" of field lines.

Force between quarks is roughly constant as the separation increases.

At a separation of roughly 1 fermi there is enough potential energy in the field to create a new $q\bar{q}$ pair

The Strong Nuclear Force

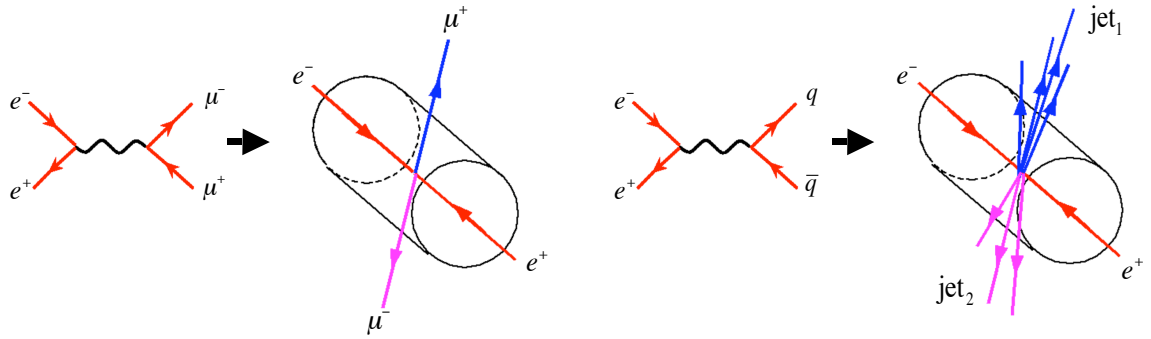
- This leads to a process of **fragmentation** and **hadronisation** :



Final state consists of a large number of colourless hadrons :

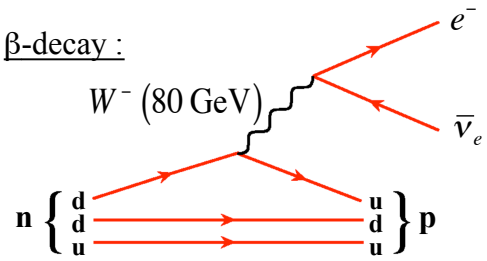
$\pi^0, \pi^+, \pi^-, \rho, \eta, p, n, \ldots$

- Reactions producing coloured particles such as quarks give rise to **jets** of hadrons :



The Weak Nuclear Force

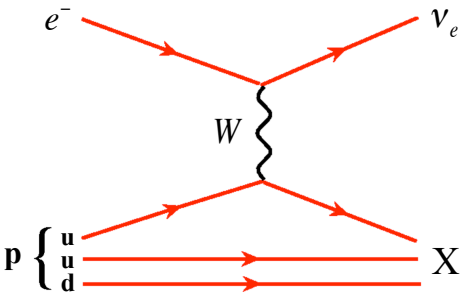
β-decay :



The large mass of the ***W*** boson makes the force :

- short range
- weak

Charged-Current (CC) :

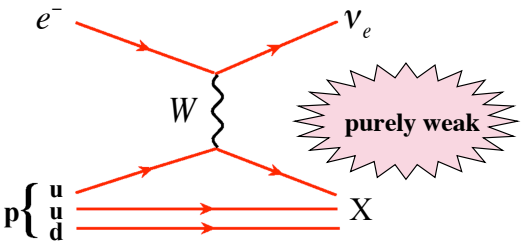


This is fundamentally the same process, with the outgoing electron replaced by an incoming electron.

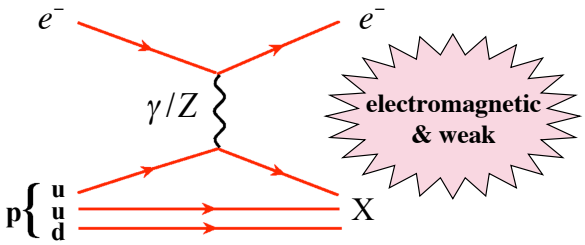
This is the corresponding scattering process that is measured at an electron-proton collider.

Electroweak Unification

Charged-Current (CC) :

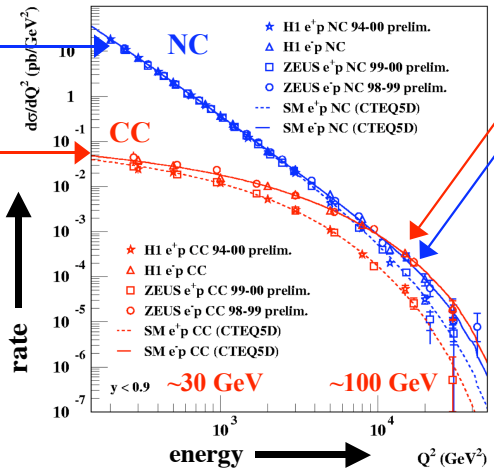


Neutral-Current (NC) :



entirely γ (electromagnetic)

entirely W (weak nuclear)



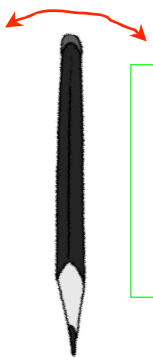
W, γ ,Z contribute equally (roughly)

At high energies the electromagnetic and weak nuclear forces appear to be two facets of the same underlying ***electroweak*** interaction.

This ***symmetry*** appears ***broken*** only at low energies.

Higgs Mechanism

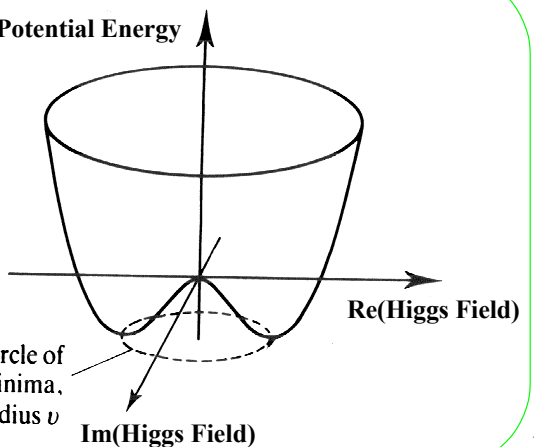
- At high energies, the electromagnetic and the weak nuclear forces appear to be unified into a single ***electroweak*** force.
- However this symmetry evident at high energies is badly broken at low energies, since the γ is massless and the **Z** weighs 100 times as much as a proton.
- The **Higgs mechanism** provides a way-out. The underlying electroweak symmetry was hidden when the universe selected (randomly ?) a value for the Higgs field.



The underlying physics is symmetric.

But the universe :

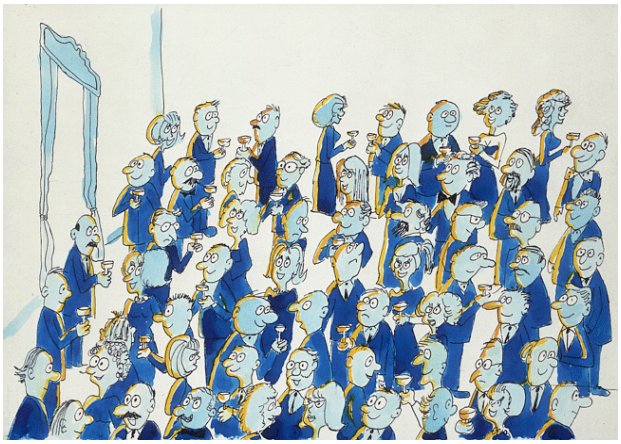
- selects one particular direction for the pencil to fall
- selects one particular value for the Higgs field



Higgs Mechanism

- What's the Higgs field got to do with electroweak symmetry breaking ?
- It gives the particles (especially the ***W*** and ***Z*** boson) their masses.
- How ?

★ Vacuum Higgs field :



★ Particle in a Higgs field :

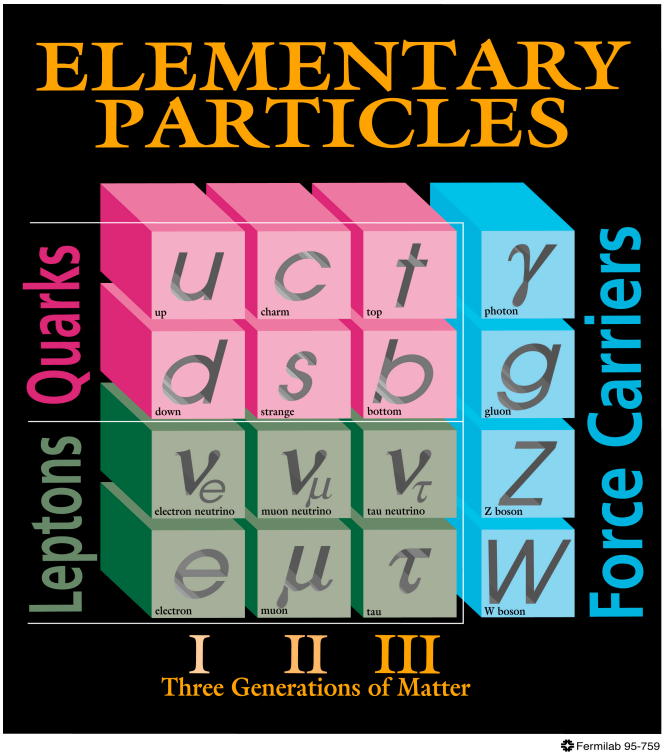
Higgs Mechanism

★ Apply a perturbation to the field :

★ And ... what's this ?

★ But we haven't found the Higgs boson yet - we are building a new accelerator to try and find it.

The "Standard Model"



\+ H higgs

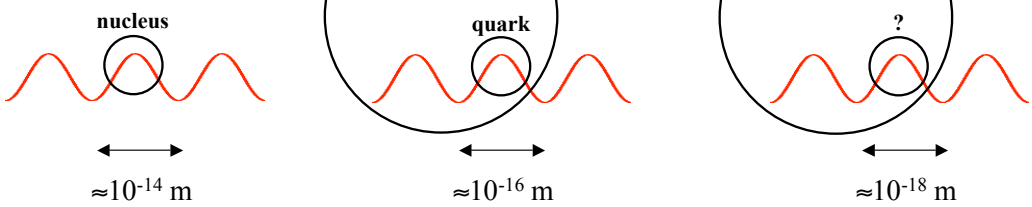
But :

- Why 3 matter generations ?
- Why the observed pattern of particle masses ?
- Are the neutrinos really massless? (the latest evidence indicates not).
- Can all the forces be unified into a single underlying force ?
- Where does gravity fit in ?
- Why is there an excess of matter over anti-matter in the known universe ?
- Why does **Q(proton) = Q(e^+)** ?
- ..... etc.

Why is Particle Physics also High Energy Physics ?

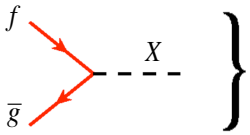
- De Broglie :

$$\lambda = h/p$$



- Einstein :

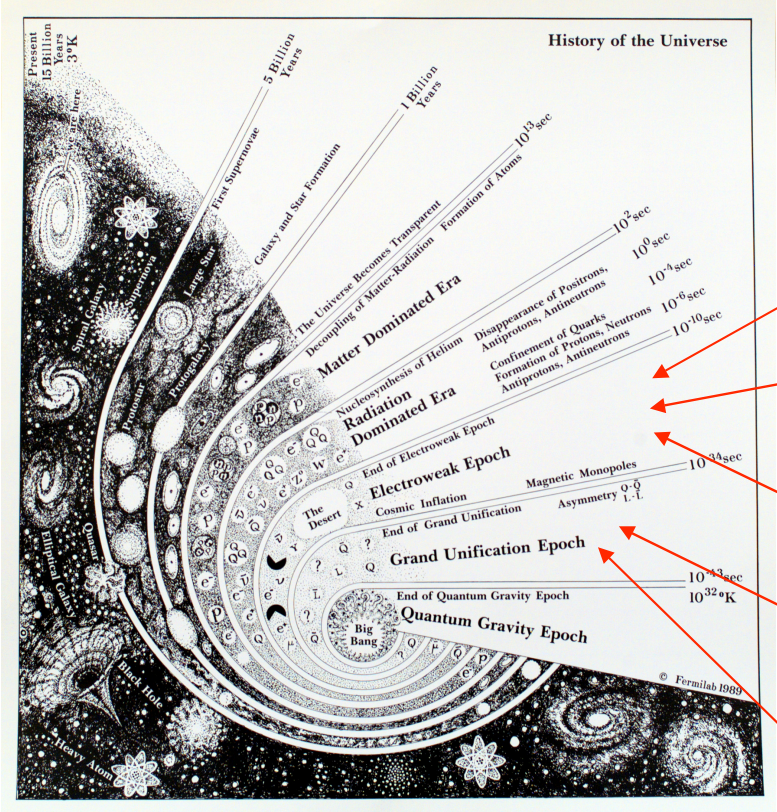
$$E = mc^2$$



→ Most likely when $E_f + E_{\bar{g}} = m_X$

→ Large energies are needed to create the most massive of the fundamental particles : top quark, Higgs boson (?), new particles (?)

Particle Physics & The Early Universe



Higher energies correspond to earlier epochs after the Big Bang :

Reach of current collider experiments.

What makes up the dark matter in the universe ?

What is the source and composition of the highest energy cosmic rays ?

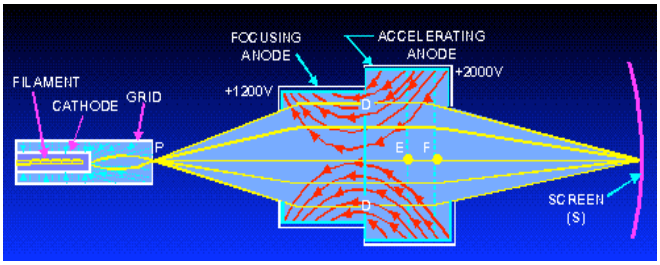
Why is there an excess of matter over anti-matter in the universe ?

Do protons decay ?

Part 2 :
Accelerators & Detectors

Particle Accelerators

- **Cathode ray tube** : accelerates electrons to energies of 10 KeV or so.
- Even the largest accelerators start out with something similar.
- Acceleration up to higher energies uses electromagnetic waves (either travelling or standing waves) rather than electrostatics.
- **Linear accelerators** can reach up to 25 MeV/m :



Medical linacs generate electron or photon beams up to 25 MeV over a few metres.

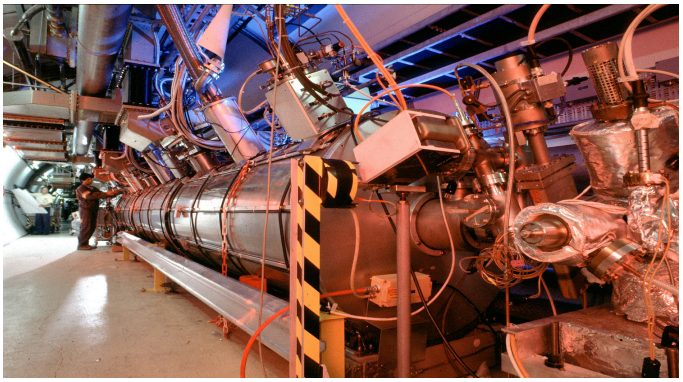
- But ... would take 40 km to reach 1000 GeV !
- Solution : bend the accelerator into a circle. "**Synchrotron**".
- Particles accelerated over effective distances of millions of km !

Particle Accelerators

Synchrotron : circular particle accelerators.

Strong magnets required to bend particles in a circle.
Magnetic field : $\mathbf{B \propto 1/R}$

When charged particles accelerate they loose energy through radiation, which must be replaced.
Centripetal acc. = $\mathbf{v^2/R}$



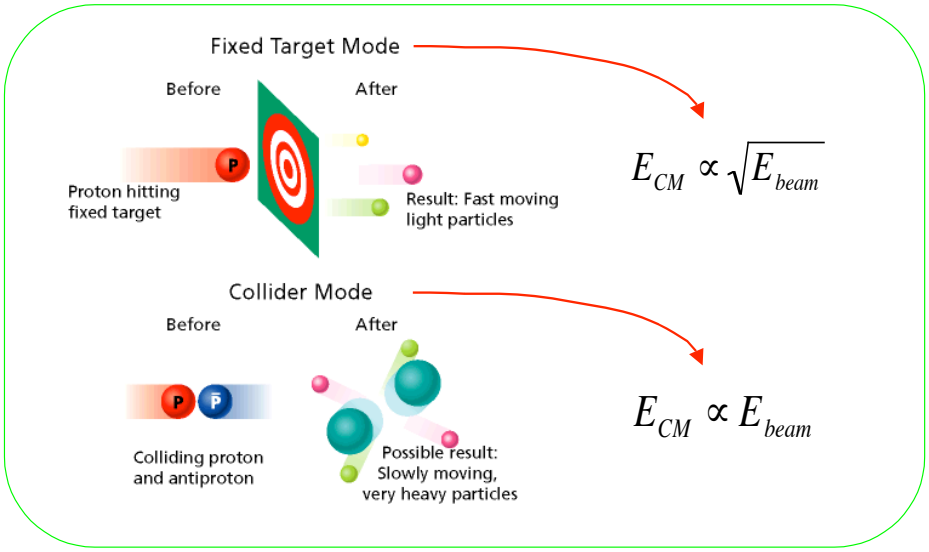
⇒ Make **R** as large as possible.

Large **E**lectron **P**ositron Collider at CERN : **R = 4.3 km Energy → 205 GeV**
Large **H**adron **C**ollider (proton-proton) **: Energy → 14 TeV (2007-8)**

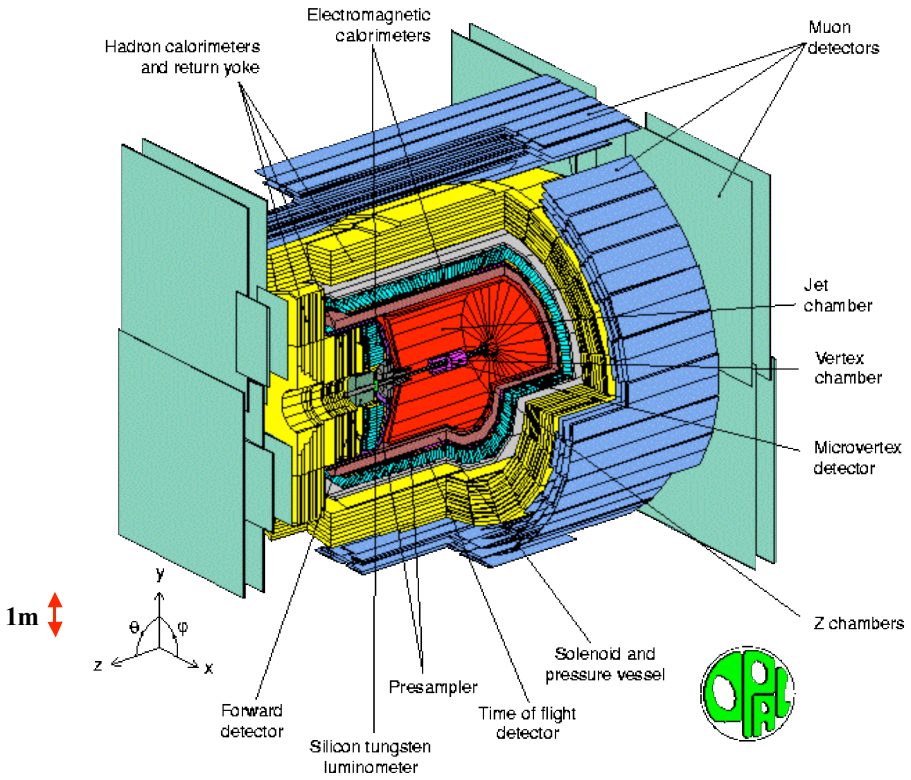
1 TeV = 1000 GeV

Particle Accelerators

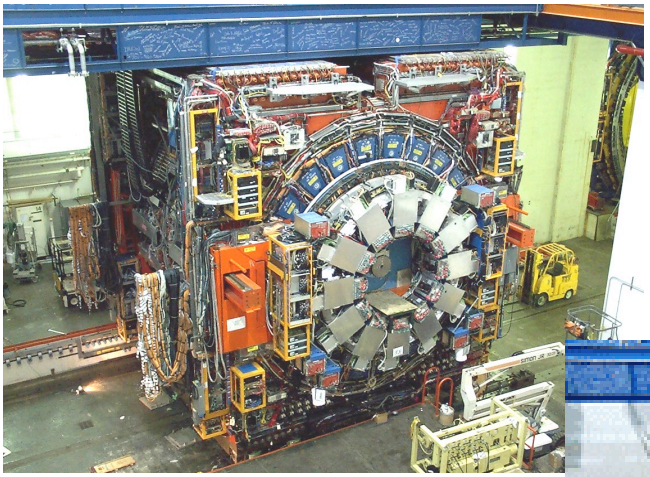
- Electron and positron beams are a few **μm** in diameter (much smaller than a human hair). Extremely difficult to bring into collision.
- Why not smash a single beam into a target ?
- Since the electrons and positrons are moving at **99.999...%** of the speed of light, we need to use special relativity to calculate the energies of the collisions.



Particle Detectors

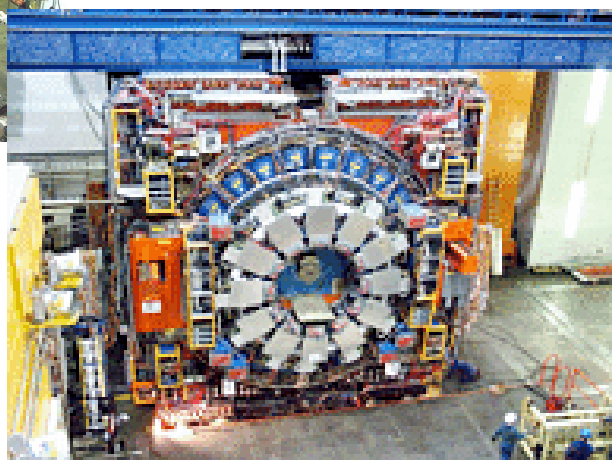


Particle Detectors



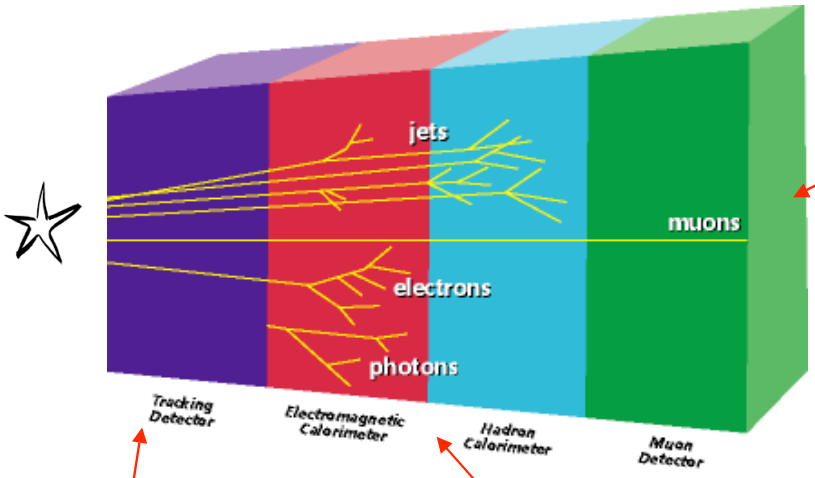
⇐ **CDF** Detector at the Tevatron proton anti-proton collider at Fermilab, Chicago.

ANIMATION



- Similar in very many respects to the **OPAL** detector at **LEP**.
- Both are "general purpose" detectors designed to capture as many of the collision products as possible.

Detecting Particles : In a Nutshell



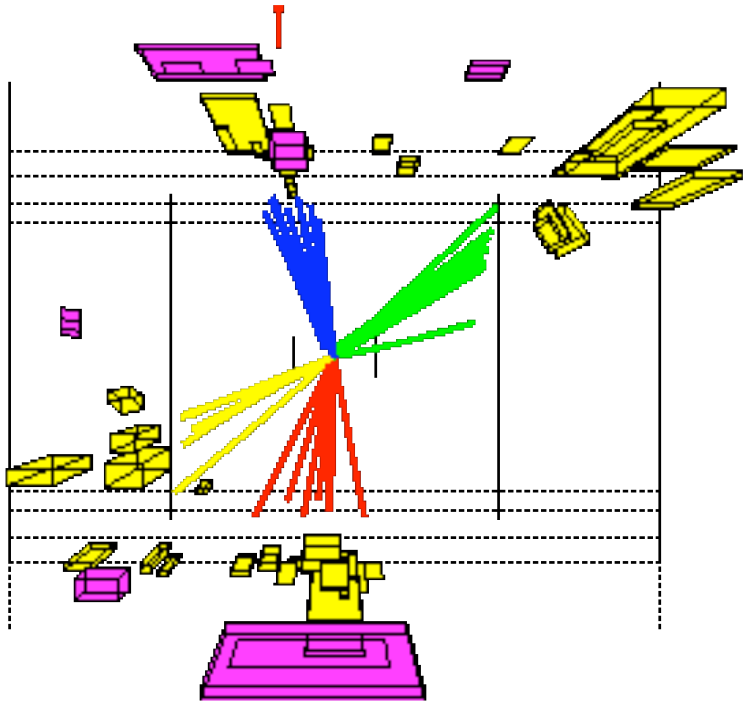
Muons are very penetrating but still leave tracks.

- Non-destructive measurement, for example through ionising effects of moving particles.
- Use as little material as possible (gas, thin silicon wafers).
- Charged particles only.

- Particles give rise to "showers" of secondary particles through nuclear interactions in dense materials.
- Destructive (absorptive) measurement.
- Use dense materials to absorb. Sensitive elements to record shower.

OPAL Event Picture

ANIMATION



Summary

- The **Standard Model** of particle physics is amazingly successful. It enables us to understand almost all the properties and interactions of the fundamental particles that we know. It is extremely predictive.
- But, we know it is logically incomplete without a symmetry breaking mechanism such as the **Higgs mechanism**.
- The **Higgs boson**, or some other new particle or interaction must be discovered at energies around **1 TeV.**
- The **Large Hadron Collider** and experiments are being built to explore this region.
- What lies beyond that ?
- What is the ultimate theory of everything ?

Superstrings in 11 dimensions ?